IMPERVIOUS SURFACE AREA AS A PREDICTOR OF THE EFFECTS OF URBANIZATION ON STREAM INSECT COMMUNITIES IN MAINE, U.S.A.

CHANDLER C. MORSE, ALEXANDER D. HURYN* and CHRISTOPHER CRONAN
Department of Biological Sciences, University of Maine, Orono, Maine, U.S.A.
(author for correspondence, e-mail: huryn@maine.maine.edu)*

(Received 23 January 2002; accepted 22 October 2002)

Abstract. The influence of urbanization on stream insect communities was determined by comparing physical, chemical, and biological characteristics of streams draining 20 catchments with varying levels of urban land-cover in Maine (U.S.A). Percent total impervious surface area (PTIA), which was used to quantify urban land-use, ranged from ∼1–31% among the study catchments. Taxonomic richness of stream insect communities showed an abrupt decline as PTIA increased above 6%. Streams draining catchments with PTIA < 6% had the highest levels of both total insect and EPT (Ephemeroptera + Plecoptera + Trichoptera) taxonomic richness. These streams contained insect communities with a total richness averaging 33 taxa in fall and 31 taxa in spring; EPT richness ranged from an average of 15 taxa in fall and 13 taxa in spring. In contrast, none of the streams draining catchments with 6–27% PTIA had a total richness > 18 taxa or an EPT richness > 6 taxa. Insect communities in streams with PTIA > 6% were characterized by the absence of pollution-intolerant taxa. The distribution of more pollution-tolerant taxa (e.g. *Acerpenna* (Ephemeroptera); *Paracapnia, Allocapnia* (Plecoptera); *Optioservus, Stenelmis* (Coleoptera); *Hydropsyche, Cheumatopsyche* (Trichoptera)), however, showed little relation to PTIA. In contrast to the apparent threshold relationship between PTIA and insect taxonomic richness, both habitat quality and water quality tended to decline as linear functions of PTIA. Our results indicate that, in Maine, an abrupt change in stream insect community structure occurs at a PTIA above a threshold of approximately 6% of total catchment area. The measurement of PTIA may provide a valuable tool for predicting thresholds for adverse effects of urbanization on the health of headwater streams in Maine.

Keywords: bioassessment, biomonitoring, urban land use, urban streams, stream insects

1. Introduction

Urban land-use covers at least 26 million hectares of the U.S.A. (Vesterby, 1994). This area is expected to increase rapidly within the next few decades, primarily due to the expansion of suburbs that surround centralized metropolitan areas (O'Hara, 1997). The expansion of suburbs – a process popularly known as 'urban sprawl' – results in the rapid conversion of agricultural and forested lands to urban land-use (Peiser, 1989).

Urban land-use is associated with physical, chemical and biological changes to stream ecosystems. Physical changes include channel widening and incision, and increased rates of erosion and sedimentation (Leopold, 1968; Hammer, 1972;

Environmental Monitoring and Assessment **89:** 95–127, 2003.

TABLE I

Summary of studies of the effect of urbanization and PTIA on the stream insect communities

Source	State/ province	PTIA threshold	Invertebrate community response
Klein (1979)	MD	10%	Decreased diversity with urbanization
Benke *et al*. (1981)	GA	n.d.[a]	Decreased diversity with urbanization
Pratt *et al*. (1981)	MA	n.d.	Decreased diversity with urbanization; loss of sensitive taxa
Duda *et al*. (1982)	NC	n.d.	Decreased diversity and loss of sensitive taxa with urbanization; shift toward tolerant taxa (Chironomidae, Oligochaeta)
Whiting and Clifford (1983)	AB	n.d.	Increased density and decreased diversity with urbanization; loss of sensitive taxa; shift toward tolerant taxa (Tubificidae, Chironomidae)
Pedersen and Perkins (1986)	WA	n.d.	Decreased functional diversity with urbanization
Jones and Clark (1987)	VA	15–25%[b]	Decreased diversity with urbanization; increased relative abundance of tolerant taxa (Chironomidae)
Schueler and Galli (1992)[c]	MD	15%	Decreased diversity with urbanization
Garie and MacIntosh (1986)	NJ	n.d.	Decreased population density and decreased richness and loss of sensitive taxa with urbanization; shift in dominance toward tolerant taxa (Tubificidae, Chironomidae)
Shaver *et al*. (1995)	DE	8–15%	Decreased diversity with urbanization
Maxted (1996)	DE	10–15%	Loss of sensitive taxa with urbanization; shift toward tolerant taxa (Chironomidae)
May (1997)	WA	5–10%	Decreased multimetric scores with urbanization

[a] n.d. = No data.
[b] Conversion of measure of urban intensity by Jones and Clark (1987) to PTIA using Schueler (1994).
[c] From Schueler (1994).

Whipple *et al*., 1981; Arnold *et al*., 1982; Booth, 1990). These physical changes are related to alterations of the hydrologic regime (Hollis, 1975; Ragan *et al*., 1977; Booth, 1991). Chemical changes include elevated levels of organic compounds, suspended and dissolved solids, nutrients (nitrogen and phosphorus), and heavy metals (Porcella and Sorenson, 1980). Physical and chemical changes that occur as a stream catchment is urbanized are correlated with biological changes such as alterations in the community composition of stream insects (Table I).

Schueler (1994) synthesized the available information concerning the effects of urbanization on stream ecosystems and concluded that the percentage of the total impervious area (PTIA) within a stream's catchment may serve as a predictor of environmental degradation. He reported that stream health, as indicated by changes in water and habitat quality, hydrology, and biodiversity, degraded rapidly as PTIA increased to 10–20%, suggesting a possible threshold effect. Schueler (1992) had previously proposed three categories of environmental stress that appeared to be related to PTIA: stressed streams with 5–10% PTIA within their catchment, impacted streams with 11–25% PTIA, and degraded streams with 26–100% PTIA. His later review supported these categories and he suggested the need for further research in varying locations to assess the potential for using PTIA to predict the effects of future changes in land use on aquatic resources (Schueler, 1994).

In this article we attempt to answer two questions. First, is increasing urbanization, as indicated by PTIA, correlated with degradation of the physical, chemical, and biological characteristics of headwater streams in Maine? Second, do adverse impacts of urbanization on streams occur at a threshold of 10–20% PTIA as suggested by Schueler (1994)? We addressed these questions by comparing insect community structure and indices of habitat and water quality among headwater streams draining 20 catchments with PTIA levels ranging from ~1 to 31% PTIA.

2. Methods

2.1. Catchment selection

The goal of the catchment selection process was to locate 20 catchments representing the range of urban land-cover occurring in southern and central Maine. Criteria for selection included stream width, depth, discharge, gradient, substrate, habitat structure, absence of obvious point sources of pollution, and geographical location. Streams were required to be perennial with cobble riffle habitat. Their channels were required to have an average width of $\leq$8 m, an average depth of $\leq$80 cm, and an overall gradient of $\leq$4.0%. To further reduce variability, catchments were selected in regional blocks that included at least one reference catchment and catchments with low, moderate, and high PTIA. Reference catchments are defined as those that are predominately forested and with <5% PTIA (Schueler, 1994). For the initial catchment selection, urban intensity was estimated from 1:24 000 scale United States Geological Survey (USGS) topographic maps, *The Maine Atlas and Gazetteer* (DeLorme, 1997), and field inspection.

Twenty catchments, from over 300 assessed, met the selection criteria. Regional blocks were selected in the vicinity of the cities of Bangor (44°45′N, 68°46′W; area ~90 km^2, population ~33 000 people), Anson/Madison (44°48′N, 69°53′W; ~24 km^2 and ~21 000 people), Augusta (44°18′N, 69°47′W; ~143 km^2 and ~21 000 people), and South Portland (43°38′N, 70°14′W; ~31 km^2 and ~23 000

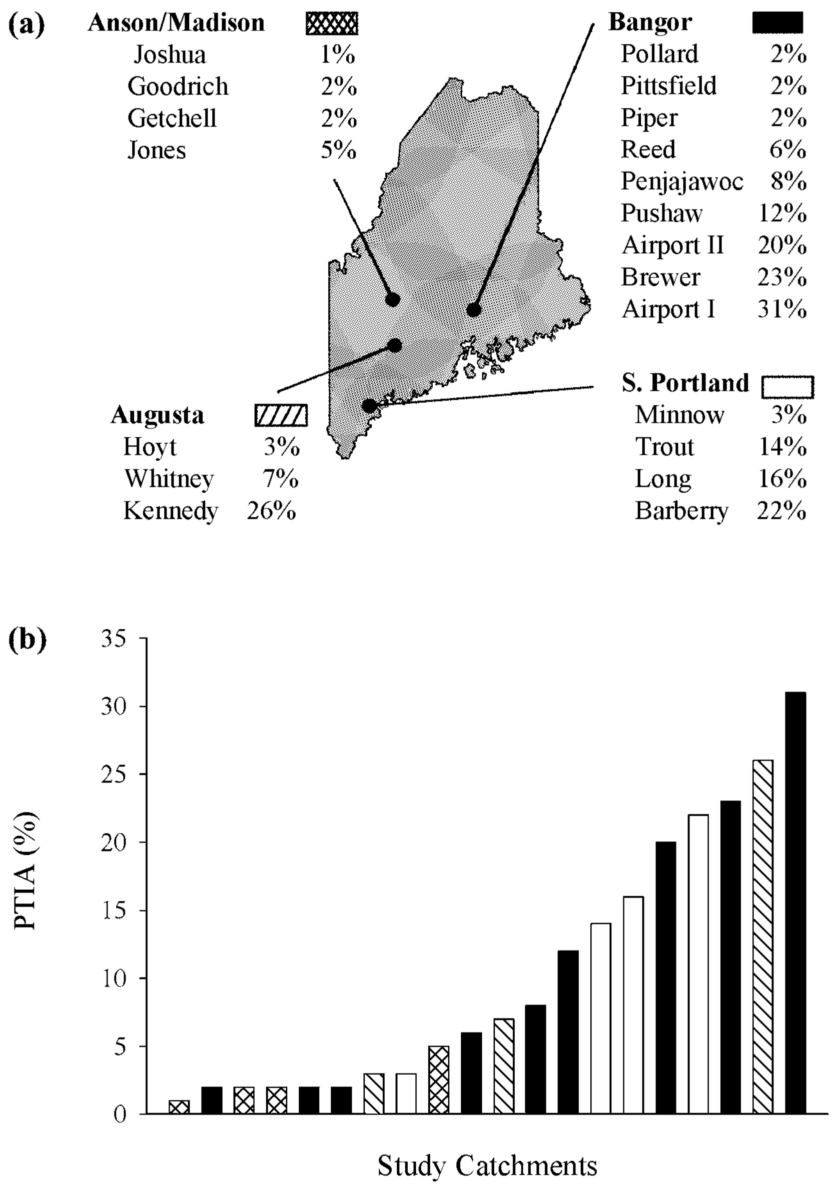

Figure 1. (a) Map of Maine showing locations of the study catchments and their PTIA, (b) Urban gradient represented by the study catchments. Catchments are in order of increasing PTIA and are coded by region corresponding to Figure 1a.

TABLE II

Estimates of percent impervious surface area (PTIA) associated with common residential dwelling densities. TR-55 factors were reported in Soil Conservation Service (1975) and HSPF Model and Olympia Study factors were reported in City of Olympia (1994)

Dwelling density	PTIA			
	This study	TR-55	HSPF Model[a]	Olympia Study[a]
Low-density (<1 unit/acre)	13%	20%	10%	n.a.
Mid-density (4 units/acre)	28%	38%	40%	40%
High-density (8 units/acre)	32%	65%	60%	48%

[a] HSPF Model and the Olympia Report listed densities for mid-density to be 3–7 units/acre and high-density to be 8–30 units/acre.

people) (Figure 1a). All catchments are within the mixed wood plains ecological region as described by the Commission for Environmental Cooperation (1994). The Augusta and Anson/Madison catchments are in the Kennebec River drainage. The Augusta catchments are in the coastal upland region whereas the Anson/Madison catchments are in the western foothills. The Bangor catchments are in the coastal upland region of the Penobscot River drainage. The South Portland catchments are in the Fore River drainage in the coastal plain region.

2.2. Percent Total Impervious Area (PTIA)

PTIA was estimated from 1:7200 scale aerial photographs that were taken from 1991 to 1998 (Natural Resource Conservation Service, Maine). Catchment boundaries were delineated from USGS topographic maps (1:24 000) using the watershed divide technique (Stanford, 1996) and then transcribed onto aerial photographs using plastic overlays. Areas of obvious impervious surfaces, such as parking lots and industrial buildings, were measured with a planimeter. Areas of apparently homogenous urban land-cover were also measured. The PTIA for these latter areas, primarily residential neighborhoods consisting of one, 1/2, 1/4, and 1/8 acre lots, was estimated using an empirically derived impervious surface factor. Impervious surface factors have been reported from other regions of the U.S.A (Soil Conservation Service, 1975; City of Olympia, 1994). These tend to be variable, however (Table II). In recognition of this, an impervious surface factor was calculated specifically for this study by selecting small study areas of homogenous urban land-cover and directly measuring the area of impervious surfaces in the field (Morse, 2001). PTIA for entire catchments was calculated using the following equation:

$$\mathrm{PTIA} = ((\mathrm{LIA}) + (\mathrm{HULC} \times \mathrm{IF}))/\text{Total catchment area}\ ,$$

where

LIA	=	Area of large impervious surfaces;
HULC	=	Area of homogenous urban land-cover;
IF	=	An empirically derived impervious surface factor.

2.3. Land-cover classification

A GIS map based on the Maine GAP classification (http://janus.state.me.us/ifw/index.htm; Hepinstall *et al.*, 1999) provided the area of each catchment that could be classified as urban, forest, agriculture, or wetland land-cover. The Maine GAP classification is a raster image of a 38-category land-cover classification based on Landsat TM satellite data (30 m pixel resolution) from 1991 and 1993 (Hepinstall *et al.*, 1999). For this study, the 38 categories of land cover were reduced to four inclusive categories (urban, forest, agriculture, and wetland). The areas of the study catchments were digitized from 1:24 000 scale USGS topographic maps and their proportional land cover was classified.

Aerial photointerpretation and field surveys were used for a qualitative assessment of urban land-cover. Urban land-cover was categorized as: light residential (lots of 1 to 1/2 acre in size), moderate residential (1/2 acre lots), heavy residential (1/4 acre lots), commercial (e.g. shopping centers), industrial (e.g. rail yards, factories) and airports. Specific impervious surface factors were applied to each category (Morse, 2001).

2.4. Habitat quality

A 100 m study reach was located on each stream near the outlet of its catchment. Study reaches were at least 10 m from any road crossing, culvert, or stream junction. Each reach was divided into 10 m sections using transects placed perpendicular to the stream flow (11 transects total). Bankfull width and depth, wetted width and depth, bank erosion and angle, percent substrate, and riparian width and forest-type were measured at each transect during August to October 1998. The gradient of each reach was also measured using a Sunuto® clinometer. Water velocity was measured with a Globe® flowmeter. Discharge was measured using the velocity-area method as described by Gore (1996). All measurements were made a minimum of 48 hr after the last rainfall.

Stream habitat cover was quantified from maps prepared following Meader *et al.* (1993), Platts *et al.* (1983), and May *et al.* (1997). The Qualitative Habitat Index (QHI; Barbour and Stribling, 1994) and the Stream Reach Inventory and Channel Stability Index (SRICSI; Pfankuch, 1975) were used to assess the physical condition of each stream. The QHI integrates 10 different metrics to yield a relative score indicating habitat quality for riffle/run prevalent streams. Metrics include evaluations of substrate availability and condition, channel condition, extent of erosion/deposition, and riparian condition. The SRICSI integrates 15 metrics to yield a relative score indicating channel stability and characteristics of erosion/deposition.

A modification of the Wolman pebble count (Wolman, 1954; Potyondy and Hardy, 1994) was used to quantify the particle size distribution of the bed material. Ten particles were randomly selected at evenly spaced intervals from 10 transects and their intermediate axes measured (Potyondy and Hardy, 1994). These data were used to estimate relative abundance of median (D_{50}) and fine (D_{10}) particle fractions.

2.5. Water quality

Water temperature, pH, dissolved oxygen (DO), specific conductance, nutrients (nitrogen and phosphorus), and total suspended solids (TSS) were measured in the summer (August–September) and fall (November) of 1998 and spring (April–May) of 1999. All measurements were made a minimum of 48 hr after the last rainfall. Temperature, pH, DO, and specific conductance were measured shortly before dawn at the upstream boundary of the study reach using hand-held YSI® meters. TSS were filtered in the field from grab samples of stream water (250–1000 mL) using Advantec® GF75 filters with a nominal pore size of 0.7 μm. The filtrate was collected in 250 mL acid-washed bottles and returned on ice to the Maine Soil Testing Laboratory (Deering Hall, University of Maine, Orono, Maine 04469) where they were analyzed for NO_3-N and soluble reactive phosphorus (SRP) using an Alpkem® flow-injection analyzer with detection limits of 0.005 and 0.05 mg L^{-1}, respectively. Total phosphorus (TP) was measured using a Jarrell-Ash® TJA 975 spectrophotometer with a detection limit of 0.05 mg L^{-1}. The Maine Soil Testing Laboratory analyzes standards of known concentrations (certified by the National Institute of Standards and Testing) between every 10–15 field samples to verify the accuracy of their analyses.

2.6. Insect community structure

Benthic insects were sampled during fall (November–December 1998) and spring (April–May 1999). Three samples were taken from randomly selected locations within riffle habitats using a Surber sampler fitted with a 230 μm mesh net. The material collected in the net of the Surber sampler was rinsed through a 500 μm sieve bucket. The large debris was discarded and the remaining material was preserved in 70% ethanol. Insects were later removed from the samples by hand and identified to the lowest practical taxonomic level using Merritt and Cummins (1996), Thorp and Covich (1991), Wiggins (1977), and Stewart and Stark (1993). Most taxa were identified to genus. However, the Collembola were identified to order, the Simuliidae (Diptera) were identified to family, and the Chironomidae (Diptera) were identified to subfamily or tribe. Samples with an extraordinary amount of organic material or densities of insects were subsampled using a Folsom plankton sample-splitter. No less than 100 organisms were identified from any sample, however.

Data for benthic insects were used to calculate taxon density (as average number of individuals per sample), number of unique taxa (taxa present in only one sample), total richness (number of taxa identified per sample), and the EPT Index. The EPT Index is routinely used as a measure of relative levels of anthropogenic stress on benthic insect communities and is calculated as the sum the number of taxa from the orders Ephemeroptera, Plecoptera, and Trichoptera (Barbour *et al.*, 1999).

3. Analyses

The relationship between PTIA and the various physical, chemical and biological attributes of the study streams was examined using regression analysis. Specific independent variables included physical channel attributes (channel morphology, QHI, SRICSI, D_{50} and D_{10} particle sizes), water quality attributes (DO, specific conductance, TSS, NO_3-N, SRP and TP, all as averages of three seasonal samples), and attributes of the benthic insect communities during fall and spring (density, total richness, and EPT Index values). The *t*-test was used to examine differences in attributes of stream insect community-structure between reference and urbanized catchments. To meet the assumptions of normality, abundance data were transformed using the $\ln(x + 1)$ transformation. Statistical significance was indicated by p values < 0.05.

4. Results

4.1. PTIA

The PTIA for the 20 study catchments ranged from a low of ~1% for Joshua Brook to a high of 31% for Airport I (Figure 1b; Table III). An extensive field survey of 300 catchments throughout the more developed portions of Maine indicated that Airport I represented the upper limit for PTIA in the state. Nevertheless, the PTIA for Airport I is considerably lower than what is found for urbanized catchments in other regions of the U.S.A. (e.g. May, 1996).

4.2. Land-use classification

Land-use classification confirmed that the eight catchments designated as reference catchments (PTIA < 5%) were predominately forested, with proportions of forest cover ranging from 58% for Piper Brook to 92% for Goodrich Brook (Figure 2). A significant relationship existed between the area of each catchment classified as urban by the Maine GAP classification and PTIA ($p \leq 0.0001$, $r^2 = 0.83$; Figure 3).

TABLE III

Environmental characteristics of the study streams and their catchments

Stream	Abbrev.	Catchment characteristics				Stream characteristics					
		Urban intensity	Land-use	Metro Area	Area (km^2)	Width (m)	Depth (cm)	Q $L\ s^{-1}$	Gradient (%)	Temp. (°C)	pH
Goodrich Brk	Good	R	FOR	Anson/Madison	4.8	4.9	30	2	2.9	9.1	7.3
Joshua Brk	Josh	R	FOR	Anson/Madison	11.7	5.6	35	1	3.0	10.0	7.3
Hoyt Brk	Hoyt	R	FOR	Augusta	5.9	6.3	34	104	3.5	8.7	7.5
Piper Brk	Piper	R	FOR	Bangor	18.3	6.3	41	29	2.6	9.6	7.4
Pittsfield	Pitt	R	FOR	Bangor	9.9	5.2	43	39	3.1	unavail.	7.6
Pollard Strm	Poll	R	FOR	Bangor	18.1	7.0	41	58	2.0	13.8	7.0
Minnow Brk	Minn	R	FOR	S. Portland	3.6	5.6	30	4	0.9	10.2	7.5
Getchell Brk	Getch	L	LR	Anson/Madison	14.6	7.9	42	36	3.0	10.2	7.1
Jones Brk	Jones	L	LR	Anson/Madison	10.1	5.8	45	31	1.6	11.4	6.4
Whitney Strm	Whit	L	LR	Augusta	3.8	5.1	24	3	3.6	11.8	7.7
Reed Brk	Reed	L	LR	Bangor	5.6	9.7	39	30	4.0	8.8	8.0
Pushaw	Push	M	HR	Bangor	2.0	5.9	29	14	0.1	8.9	7.8
Penjajawoc Strm	Penj	M	COM, LR	Bangor	16.0	4.8	29	12	1.5	9.6	7.6
Trout Brk	Trout	M	COM, LR	S. Portland	5.0	3.5	30	17	1.0	9.2	7.6
Long Crk	Long	M	COM, AIR	S. Portland	5.7	3.8	32	19	0.6	10.8	7.6
Kennedy Strm	Kenn	H	IND	Augusta	2.1	5.0	33	8	2.1	12.6	7.9
Brewer	Brew	H	IND	Bangor	2.1	2.6	32	2	1.5	8.9	8.0
Airport II	AirII	H	MR, AIR	Bangor	8.8	5.9	35	5	1.5	9.4	8.0
Airport I	AirI	H	COM, AIR	Bangor	5.5	9.1	35	191	4.0	11.2	7.9
Barberry Crk	Barb	H	IND	S. Portland	2.7	7.9	26	17	3.0	10.0	7.6

Abbreviations for estimates of urban intensity are: H = high, M = moderate, L = low, and R = reference.
Abbreviations for land-use are: IND = industrial, COM = commercial, AIR = airport, LR = light residential, MR = moderate residential, HR = heavy residential, and FOR = forested.

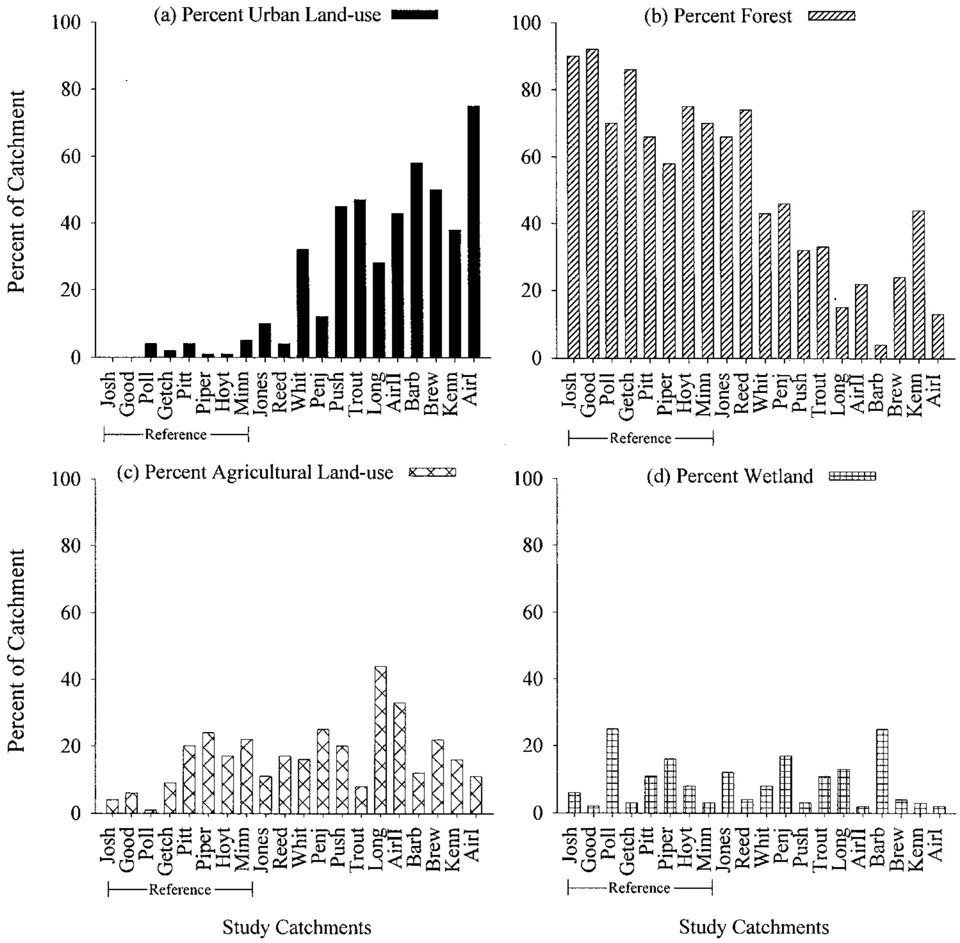

Figure 2. Proportion of study catchments under different types of land-cover: (a) percent urban land-use, (b) percent forest, (c) percent agricultural land-use, and (d) percent wetland. See Table III for key to abbreviations. Catchments are ordered by increasing PTIA.

The resulting regression equation indicated that urban land in Maine has an average PTIA of approximately 42%. There were no significant relationships between PTIA and the proportion of the catchments classified as either forest, agriculture or wetland.

4.3. Habitat Quality

As PTIA increased across study sites, riparian width decreased from a categorical class 4 (width $\geq$100 m) to 0 (width $\leq$10 m; p = <0.0001, r^2 = 0.57; Figure 4c) and bank erosion increased from a categorical class 1 (low) to 3 (high; $p \leq 0.0001$, r^2 = 0.50; Figure 4d). Other stream habitat features (e.g. pool and riffle frequency,

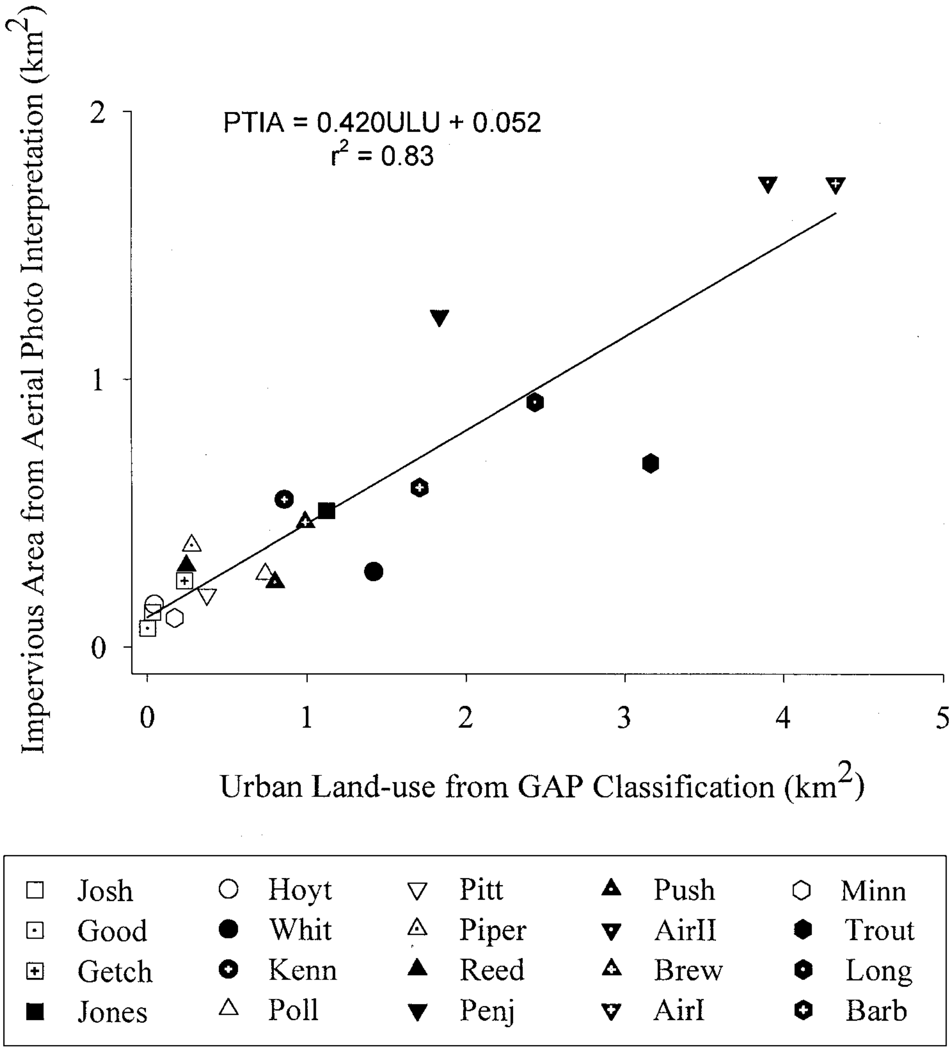

Figure 3. Relationship between the area of urban land-cover determined by aerial photointerpretation and the area of urban land-cover determined using a GIS based on the Maine GAP vegetation classification. PTIA = percent impervious surface area. ULU = area of urban land-use based on the GAP classification. Symbols are coded by shape to represent catchments within the same regional blocks: squares = Anson/Madison, circles = Augusta, triangles = Bangor, hexagons = South Portland. Open symbols are reference catchments (PTIA < 5%). See Table III for key to abbreviations.

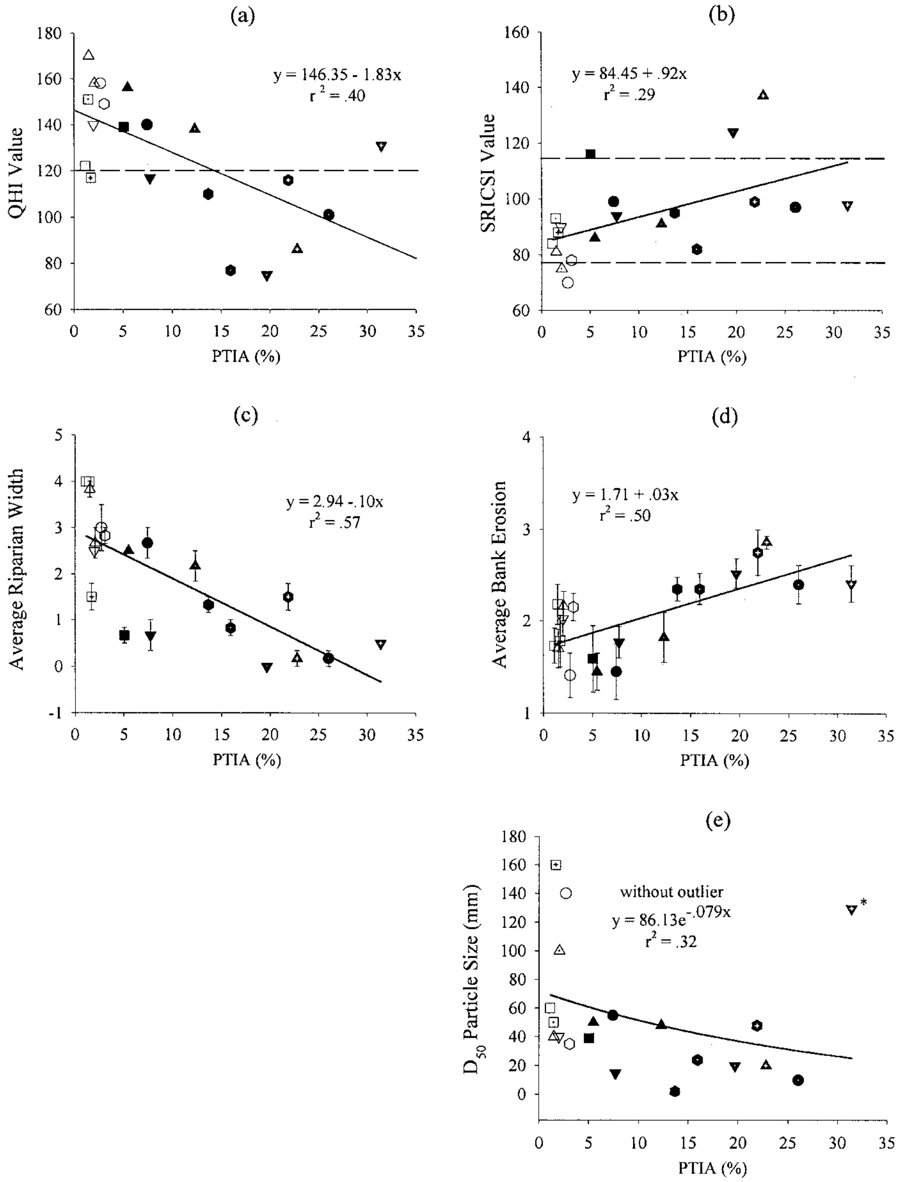

Figure 4. Relationship of physical attributes of the study reaches with catchment PTIA: (a) Qualitative Habitat Index, (b) Channel Stability Index, (c) riparian width, (d) bank erosion, (e) median particle sizes. Symbols correspond to Figure 3. Error bars indicate ± 1 S.E. Dashed lines in (a) and (b) correspond to qualitative classifications based on QHI and SRICSI index scores. QHI index ranges of 60–120 and 120–180 are considered 'marginal' and 'suboptimal', respectively. SRICSI index ranges of 39–76, 77–114, and 115–114 are considered 'good', 'fair', and 'poor', respectively. The categorical scale for (c) corresponds to $0 \leq 10$ m, 1 = 10–30 m, 2 = 30–50 m, 3 = 50–100 m, $4 \geq 100$ m. The categorical scale for (d) corresponds to 0 = no erosion evident, 1 = low level of erosion, 2 = medium, and 3 = high. The asterisk in (e) indicates a data point considered to be an outlier (see text).

riffle to pool ratios) and channel dimensions (e.g. width to depth ratios) were not significantly related to PTIA.

QHI values were negatively related to PTIA ($p = 0.003$, $r^2 = 0.40$; Figure 4a). Notable outliers included Airport I, with a QHI value (131) much greater than would be predicted by the regression equation, and Long Creek (77), Airport II (86), and Brewer (75), which had QHI values that were lower than would be predicted. On the basis of the guidelines recommended for the QHI by Barbour and Stribling (1994), the habitat condition for all 20 study streams is categorized as 'suboptimal' (QHI = 120–180 range) or 'marginal' (QHI = 60–120).

SRICSI values were positively related to PTIA ($p \leq 0.0001$, $r^2 = 0.29$), suggesting a decrease in stream bed stability with increasing urban land-cover (Figure 4b). SRICSI values ranged from 'good' (SRICSI = 39–76; Pfankuch 1975) for streams draining reference catchments to 'fair' (SRICSI = 77–114; Pfankuch 1975) for streams draining catchments with high proportions of urban land-cover (Figure 4b). Notable outliers included Jones Brook, Airport II, and Brewer which were categorized as 'poor' (SRICSI = 115–162). These streams had a greater level of instability than would be predicted by the regression equation (Figure 4b).

The Wolman pebble count indicated an inverse exponential relationship between the D_{50} particle size and PTIA ($p = 0.0001$, $r^2 = 0.32$; Figure 4e). No significant relationship existed between the D_{10} particle size and PTIA. Airport I was not included in the analysis of the pebble count data because its channel is primarily bedrock.

4.4. Water quality

Average specific conductance ranged from 59.9 μS cm^{-1} for Pollard Stream (PTIA = 1%) to 563.4 μS cm^{-1} for Airport I (PTIA = 31%). Brewer had a specific conductance that was remarkably high compared with other streams draining catchments with similar PTIA (Figure 5a). The elevated level of specific conductance in Brewer could not be attributed to a specific source, although the study reach is in close proximity to a highway. With Brewer removed from the analysis, there was a positive relationship between PTIA and specific conductance ($p \leq 0.0001$, $r^2 = 0.74$).

Average pre-dawn DO concentrations ranged from $\sim$11 mg L^{-1} in reference catchments to 5.8 mg L^{-1} in Airport I. DO concentration was negatively related to PTIA ($p = 0.001$, $r^2 = 0.48$; Figure 5b). DO concentrations in Barberry Creek appeared to be lower than would be predicted, possibly due to the presence of a 200 m culvert 10 m upstream of the sampling reach.

Concentrations of TSS ranged from $\sim$2.0 mg L^{-1} in reference catchments to 5.0 mg L^{-1} in Barberry Creek (Figure 5c). Long Creek had a TSS concentration that was high compared with other streams (Figure 5c). This is attributed to a highway construction project in the vicinity of Long Creek at the time of

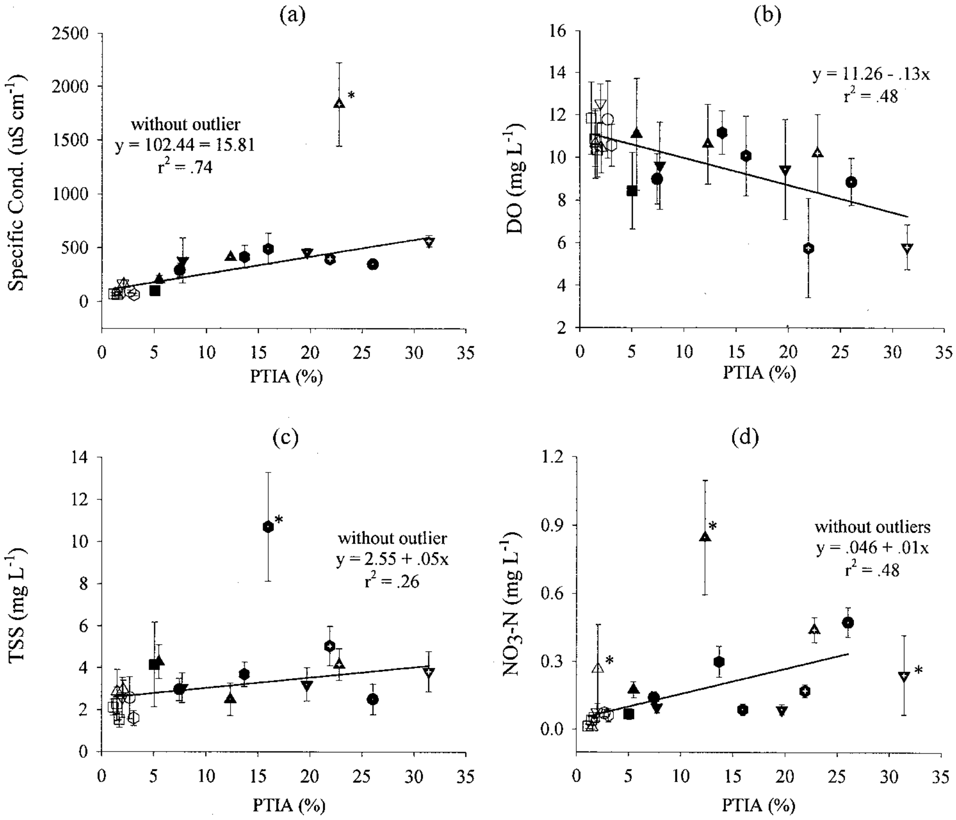

Figure 5. Relationship between water quality and catchment PTIA: (a) specific conductance, (b) dissolved oxygen, (c) total suspended solids, and (d) NO_3-N. Symbols correspond to Figure 3. Error bars indicate ± 1 S.E. Asterisks indicate data points considered to be outliers (see text).

sampling. Providing that this outlier is removed from the analysis, TSS showed a weak positive relationship with PTIA ($p = 0.025$, $r^2 = 0.26$, Figure 5c).

NO_3-N occurred at detectable levels in all streams, and average concentrations ranged from ~0.07 mg L^{-1} in reference streams to >0.7 mg L^{-1} in Pushaw. Measurements of average NO_3-N for Piper Brook, Pushaw, and Airport I were variable compared with measurements for other streams, however (Figure 5d). With these apparent outliers removed from the analysis, there was a positive relationship between NO_3-N and PTIA ($p = 0.013$, $r^2 = 0.48$). No streams contained levels of SRP that were above the detectable limit of 0.005 mg L^{-1}. Only Whitney Stream, Brewer, and Airport I contained detectable levels of TP (average TP = 0.015, 0.028, and 0.021 mg L^{-1}, respectively).

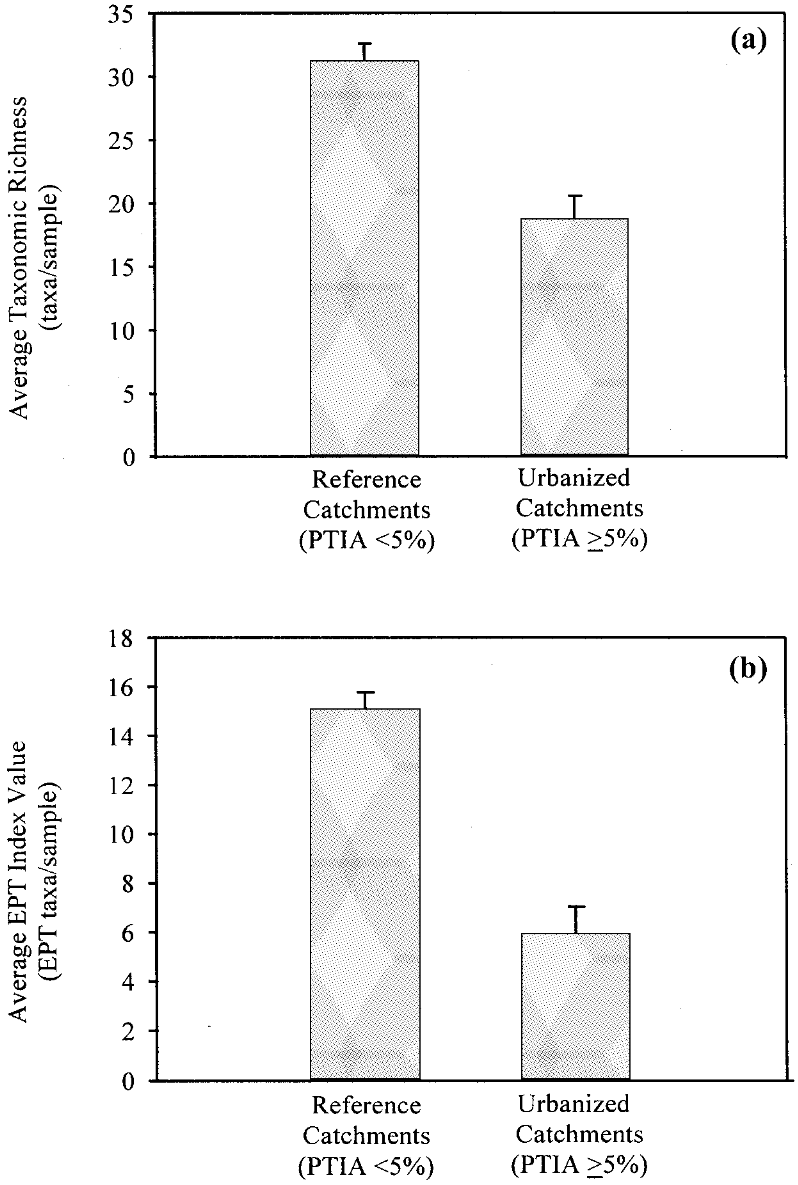

Figure 6. A comparison of (a) total taxonomic richness of stream insects and (b) EPT richness between reference and urbanized streams. N = 8 for reference catchments and n = 12 for urbanized catchments. Error bars represent ±1 S.E.

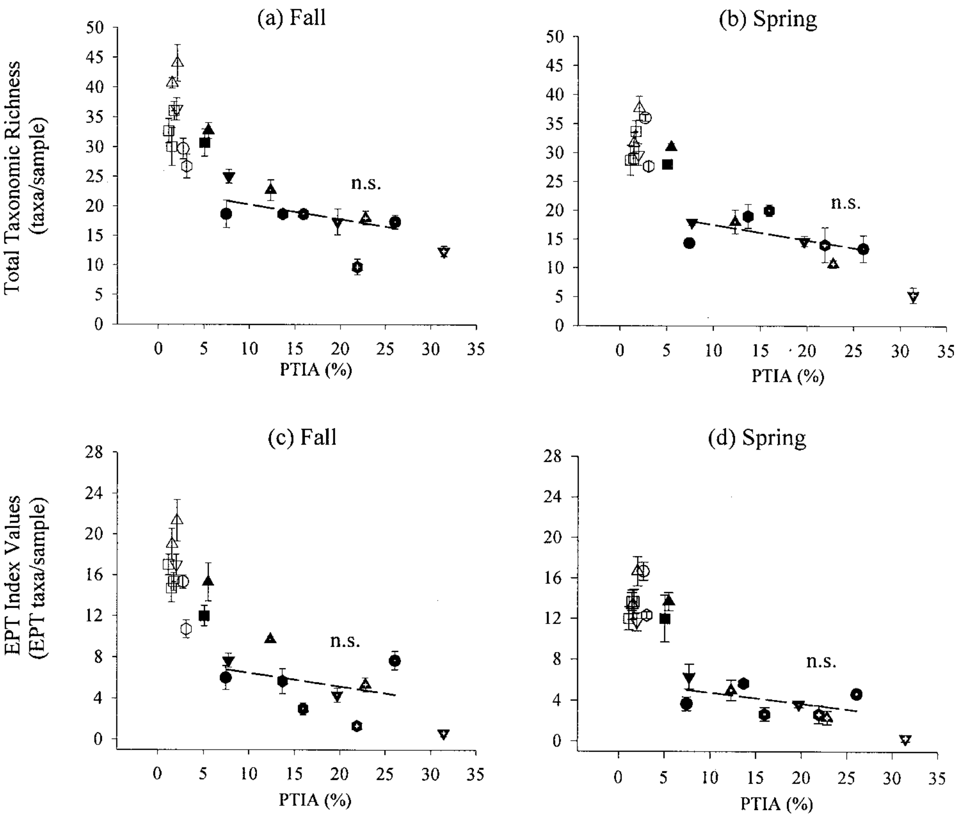

Figure 7. Relationship between PTIA and total taxonomic richness of stream insects in the (a) fall and (b) spring and EPT richness in the (c) fall and (d) spring. Symbols correspond to Figure 3. Error bars indicate ±1 S.E.

4.5. Insect community structure

A total of 93 insect taxa were identified, with 66 taxa collected in both fall and spring. Reference catchments yielded the highest taxonomic richness, averaging 34±2 (X ± S.E.) taxa in the fall and 32±1 in the spring. Catchments with the largest proportion of urban land-cover yielded the lowest richness (e.g. Barberry Creek and Airport I yielded <13 taxa). Catchments with >5% PTIA had lower total taxonomic richness than reference catchments ($p < 0.0001$, Figure 6a). Negative exponential curves described the relationship between average taxonomic richness and PTIA (fall, $p < 0.0001$, $r^2 = 0.77$; spring, $p < 0.0001$, $r^2 = 0.81$). However, within the restricted range of 6–27% PTIA, regression analysis did not indicate a significant reduction in total richness with increasing PTIA (Figures 7a and b). This indicates that once a PTIA of 6% is attained, there are no further measurable changes to the taxonomic richness of stream insects as PTIA increases to 27%.

The relationship between EPT taxonomic richness and PTIA was similar to that observed for total taxonomic richness and PTIA. The highest EPT taxonomic richness (mean of $\geq$14 taxa) occurred in reference streams; the lowest occurred in Airport I (mean of $\leq$1 taxon). Streams draining reference catchments had significantly higher levels of EPT taxonomic richness than those draining catchments with $\geq$5% PTIA ($p = < 0.0001$, Figure 6b). Negative exponential curves best described the relationship between EPT richness and PTIA (fall, $p < 0.0001$, $r^2 = 0.79$; spring, $p < 0.0001$, $r^2 = 0.82$). As observed for total taxonomic richness, catchments with PTIA ranging from 6–27% did not show a significant reduction in EPT richness with increasing PTIA (Figures 7c and d). Airport I was unusual, however, with an EPT richness well below the range expected for 6–27% PTIA (Figure 7).

The average density of insects sampled during the fall ranged from 198 individuals per sample in Brewer to 3534 individuals per sample in Piper Brook, and was negatively related to PTIA ($p = < 0.0001$, $r^2 = 0.36$; Figure 8a). The average density of insects sampled during the spring ranged from 52 individuals per sample in Airport I to 1253 individuals per sample in Long Creek. In contrast to the fall, insect density was not significantly related to PTIA during the spring (Figure 8b).

The relationship between PTIA was examined for specific 'common' taxa. Common taxa were defined as those comprising >5% of the total number of individuals identified from a sample taken in either fall or spring. A total of 43 taxa in 10 orders were classified as common. These made up no less than 87% of the total abundance of any sample taken in either season.

Among the common Ephemeroptera, densities of *Stenonema, Ephemerella*, and *Paraleptophlebia* (fall, spring) and *Serratella* (fall) were negatively related with increasing PTIA (Table IV). Other common taxa such as *Epeorus* and *Eurylophella* (fall, spring) and *Serratella* (spring) tended to be restricted to the reference sites and Jones and Reed Brooks (Figures 9 and 10) which prevented regression analysis. *Acerpenna* was the only mayfly that was present in high densities in some catchments with >6% PTIA (Figure 9).

Among the common Plecoptera, densities of *Sweltsa* (fall, spring), *Leuctra* (spring), *Paracapnia* (fall) and *Taenionema* (fall) were negatively related to PTIA (Table IV). Densities of *Allocapnia, Amphinemura* and *Isoperla* were not related to PTIA, however (Table V). The Plecoptera exhibited a distribution among the study streams that was similar to the Ephemeroptera, with the majority of taxa found only at the reference sites and Jones and Reed brooks (Figures 9 and 10). *Paracapnia* (fall) and *Allocapnia* (fall) were the only taxa occurring in high densities in streams draining catchments with PTIA > 6%. *Isoperla* and *Amphinemura* also occurred sporadically across the entire gradient of PTIA, however (Figures 9 and 10).

In contrast with the Ephemeroptera and Plecoptera, relatively high densities of Trichoptera occurred across the entire PTIA gradient (Figure 9). Among the common taxa, only *Rhyacophila* showed a negative relationship with PTIA (Table IV). *Chimarra* occurred in high density only in the reference catchments and Jones Brook and Penjajawoc stream (Figure 9), preventing regression analysis. With the

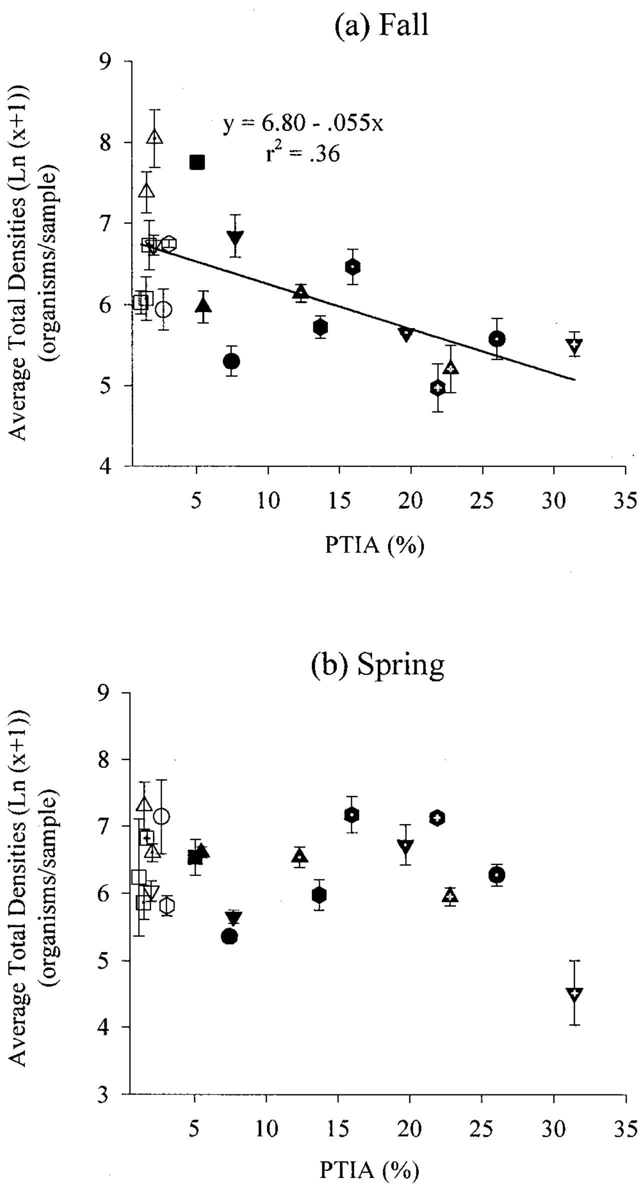

Figure 8. The relationship between PTIA and the density of benthic insects during (a) fall and (b) spring. Symbols correspond to Figure 3. Error bars indicate ±1 S.E.

TABLE IV

Common macroinvertebrate taxa with densities significantly related to PTIA (regression analysis, $p < 0.05$). Max X and Min X refer to the maximum and minimum densities occurring among all 20 study catchments. r^2, p and direction of slope (+, –) summarize the results of the regression of ln-transformed density against PTIA

Taxon	Fall					Spring				
	Max X (SE)	Min X (SE)	r^2	p	Slope	Max X (SE)	Min X (SE)	r^2	p	Slope
Ephemeroptera	488 (179)	0 (0)	0.42	0.002	–	133 (41)	0 (0)	0.41	0.002	–
Stenonema	54 (24)	0 (0)	0.29	0.014	–	12 (5)	0 (0)	0.44	0.002	–
Serratella	170 (78)	0 (0)	0.22	0.038	–	63 (13)	0 (0)	0.41	0.002	–
Ephemerella	68 (19)	0 (0)	0.47	0.001	–	39 (37)	0 (0)	0.44	0.001	–
Paraleptophlebia	222 (91)	0 (0)	0.43	0.002	–					
Plecoptera	141 (7)	0 (0)	0.54	0.000	–	115 (46)	0 (0)	0.45	0.001	–
Leuctra						80 (40)	0 (0)	0.41	0.002	–
Paracapnia	59 (49)	0 (0)	0.47	0.001	–					
Sweltsa	31 (6)	0 (0)	0.28	0.016	–	15 (6)	0 (0)	0.30	0.012	–
Taenionema	17 (6)	0 (0)	0.21	0.045	–					
Coleoptera	150 (50)	0 (0)	0.45	0.001	–	89 (19)	0 (0)	0.41	0.002	–
Ampumixis(?)						38 (14)	0 (0)	0.21	0.044	–
Promoresia	51 (14)	0 (0)	0.31	0.011	–	42 (12)	0 (0)	0.27	0.019	–
Trichoptera						346 (215)	0 (0)	0.34	0.007	–
Rhyacophila	31 (9)	0 (0)	0.46	0.001	–	21 (12)	0 (0)	0.49	0.001	–

TABLE IV
(continued)

Taxon	Fall					Spring				
	Max X (SE)	Min X (SE)	r^2	*p*	Slope	Max X (SE)	Min X (SE)	r^2	*p*	Slope
Diptera										
Chironomidae	753 (210)	56 (16)	0.24	0.030	–					
Chironomini	111 (23)	0 (0)	0.68	0.000	–	38 (20)	0 (0)	0.28	0.017	–
Tanypodinae						89 (12)	1 (0)	0.25	0.025	–
Tanytarsini	157 (122)	0 (0)	0.36	0.006	–	156 (51)	0 (0)	0.32	0.009	–
Simuliidae	1501 (1069)	0 (0)	0.38	0.004	–	763 (684)	0 (0)	0.48	0.001	–
Hexatoma	6 (3)	0 (0)	0.25	0.024	–	11 (1)	0 (0)	0.21	0.040	–
Hydracarina	62 (5)	0 (0)	0.22	0.035	–	24 (18)	0 (0)	0.34	0.007	–
Mollusca										
Pisidium	249 (220)	0 (0)	0.21	0.040	–	92 (74)	0 (0)	0.26	0.021	–
Gastropoda	23 (11)	0 (0)	0.43	0.002	+					

TABLE V

Common macroinvertebrate taxa with densities that were not significantly related to PTIA (regression analysis, $p > 0.05$). Max X and Min X refer to the maximum and minimum densities occurring among all 20 study catchments. r^2, p and direction of slope (+, –) summarize the results of the regression of ln-transformed density against PTIA

Taxon	Fall					Spring				
	Max X (SE)	Min X (SE)	r^2	p	Slope	Max X (SE)	Min X (SE)	r^2	p	Slope
Ephemeroptera										
Acerpenna	35 (9)	0 (0)	0.01	0.699	–	22 (18)	0 (0)	0.02	0.530	–
Eurylophella	21 (17)	0 (0)	0.08	0.222	–	8 (6)	0 (0)	0.07	0.254	–
Epeorus	58 (18)	0 (0)	0.11	0.162	+	33 (2)	0 (0)	0.12	0.142	–
Serratella						98 (43)	0 (0)	0.18	0.063	–
Plecoptera										
Allocapnia	79 (25)	0 (0)	0.05	0.341	–	6 (3)	0 (0)	0.19	0.056	–
Amphinemura						25 (12)	0 (0)	0.18	0.063	–
Isoperla	4 (1)	0 (0)	0.01	0.750	+	19 (6)	0 (0)	0.13	0.115	–
Leuctra	59 (24)	0 (0)	0.09	0.204	–					
Paracapnia						1 (1)	0 (0)	0.07	0.248	–
Taenionema						4 (3)	0 (0)	0.07	0.260	–
Coleoptera										
Ampumixis(?)	10 (10)	0 (0)	0.06	0.294	–					
Stenelmis	123 (56)	0 (0)	0.09	0.207	–	64 (9)	0 (0)	0.08	0.240	–
Oulimnius	9 (4)	0 (0)	0.09	0.200	–	52 (27)	0 (0)	0.12	0.130	–
Optioservus	123 (39)	0 (0)	0.18	0.062	–	42 (9)	0 (0)	0.15	0.094	–

TABLE V
(continued)

Taxon	Fall					Spring				
	Max X (SE)	Min X (SE)	r^2	*p*	Slope	Max X (SE)	Min X (SE)	r^2	*p*	Slope
Trichoptera	688 (194)	0 (0)	0.13	0.118	–					
Ceratopsyche	14 (9)	0 (0)	0.14	0.106	–					
Cheumatopsyche	138 (69)	0 (0)	0.06	0.360	–	72 (30)	0 (0)	0.08	0.213	–
Chimarra	389 (128)	0 (0)	0.14	0.104	–	163 (122)	0 (0)	0.19	0.056	–
Diplectrona	20 (6)	0 (0)	0.03	0.460	+	12 (6)	0 (0)	0.01	0.715	+
Dolophilodes	53 (51)	0 (0)	0.15	0.092	–	1 (1)	0 (0)	0.13	0.126	–
Glossosoma	60 (21)	0 (0)	0.05	0.327	–	27 (8)	0 (0)	0.00	0.096	+
Hydropsyche	227 (61)	0 (0)	0.01	0.765	–	75 (53)	0 (0)	0.00	0.970	–
Lepidostoma	17 (11)	0 (0)	0.11	0.157	–	24 (21)	0 (0)	0.04	0.401	–
Diptera	2364 (180)	74 (37)	0.13	0.065	–	1196 (347)	29 (5)	0.00	0.802	–
Chironomidae						1046 (103)	28 (5)	0.02	0.603	+
Diamesinae	105 (9)	0 (0)	0.10	0.165	+	13 (8)	0 (0)	0.04	0.396	+
Orthocladiinae	398 (134)	27 (15)	0.12	0.129	–	1010 (98)	20 (6)	0.00	0.799	+
Tanypodinae	140 (47)	2 (1)	0.02	0.527	–					
Antocha						202 (29)	0 (0)	0.01	0.734	+
Antocha	93 (10)	0 (0)	0.08	0.215	+					
Chelifera	17 (16)	0 (0)	0.01	0.659	+	48 (10)	0 (0)	0.00	0.827	–
Hemerodromia	76 (34)	0 (0)	0.01	0.755	–	36 (10)	0 (0)	0.12	0.139	–
Crustacea										
Caecidotea	27 (13)	0 (0)	0.08	0.235	+	37 (21)	0 (0)	0.09	0.199	+
Gammarus	37 (9)	0 (0)	0.01	0.678	+	25 (9)	0 (0)	0.03	0.460	+
Oligochaeta	28 (19)	1 (1)	0.07	0.277	+	122 (19)	11 (4)	0.19	0.056	+
Gastropoda						4 (1)	0 (0)	0.02	0.531	–

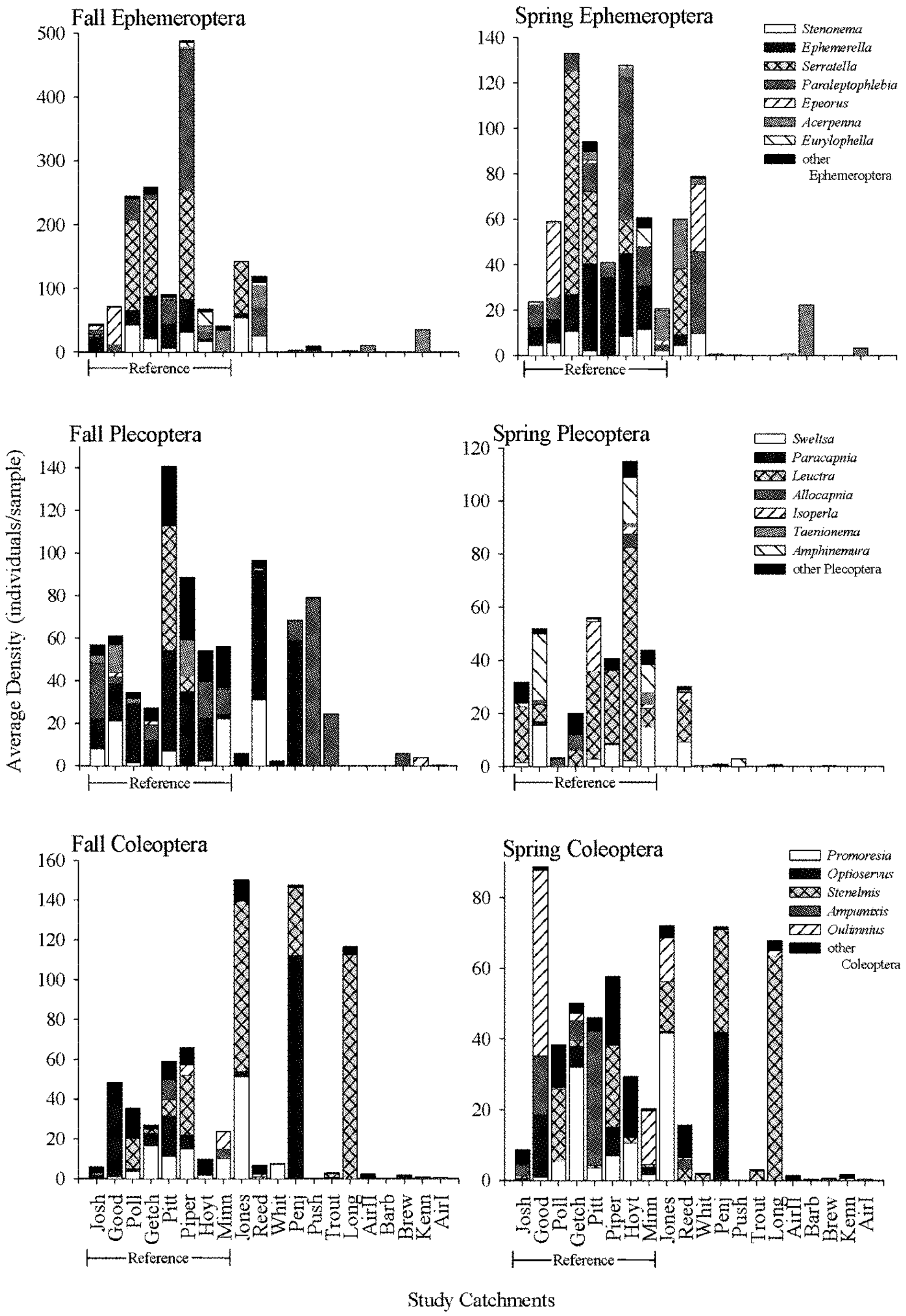

Figure 9. Comparisons of the densities of common taxa of Ephemeroptera, Plecoptera, Coleoptera, Trichoptera, Diptera and the Oligochaeta during fall and spring. See Table III for key to abbreviations. Catchments are in order of increasing PTIA. Stacked bars reflect densities of individual taxa. Maximum bar height reflects the total density for each order.

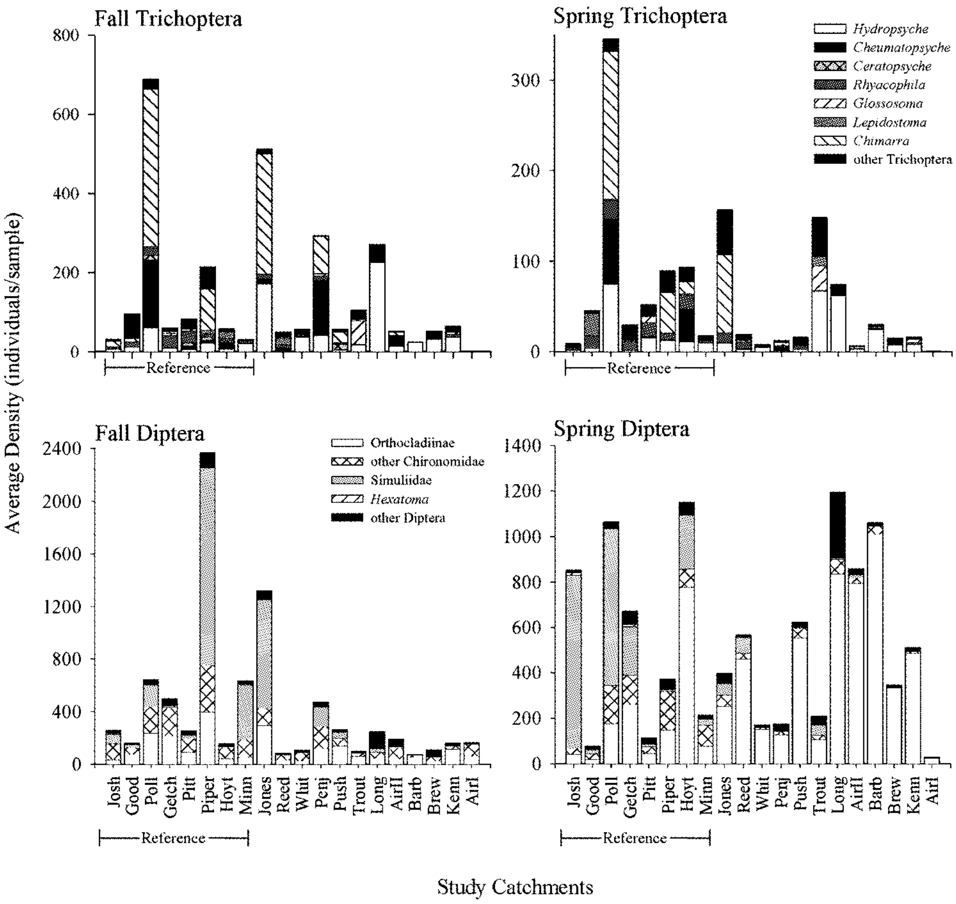

Figure 9. (continued)

exception of *Hydropsyche* and *Cheumatopsyche*, the remaining common trichopteran taxa were found only sporadically and failed to conform to any pattern related to PTIA (Table V; Figures 9 and 10). Both *Hydropsyche* and *Cheumatopsyche* occurred in relatively high densities across the PTIA gradient, and were the most abundant trichopterans in streams draining catchments with >6% PTIA (Figures 9 and 10). Although uncommon, densities of the Megaloptera (*Nigronia* and *Sialis*) showed a negative relationship with PTIA (fall, $p = 0.012$, $r^2 = 0.30$; spring, $p = 0.008$, $r^2 = 0.34$).

The common Coleoptera were represented by the Elmidae. Densities of the elmid beetles *Promoresia* (fall, spring) and *Ampumixis* (spring) showed a negative relationship with increasing PTIA (Table IV). *Ampumixis* is reported from streams in the western U.S.A., and the identification of this genus from Maine should be considered tentative (Merritt and Cummins, 1996). The elmid beetle *Oulimnius* was largely restricted to reference catchments and Jones and Reed brooks (Fig-

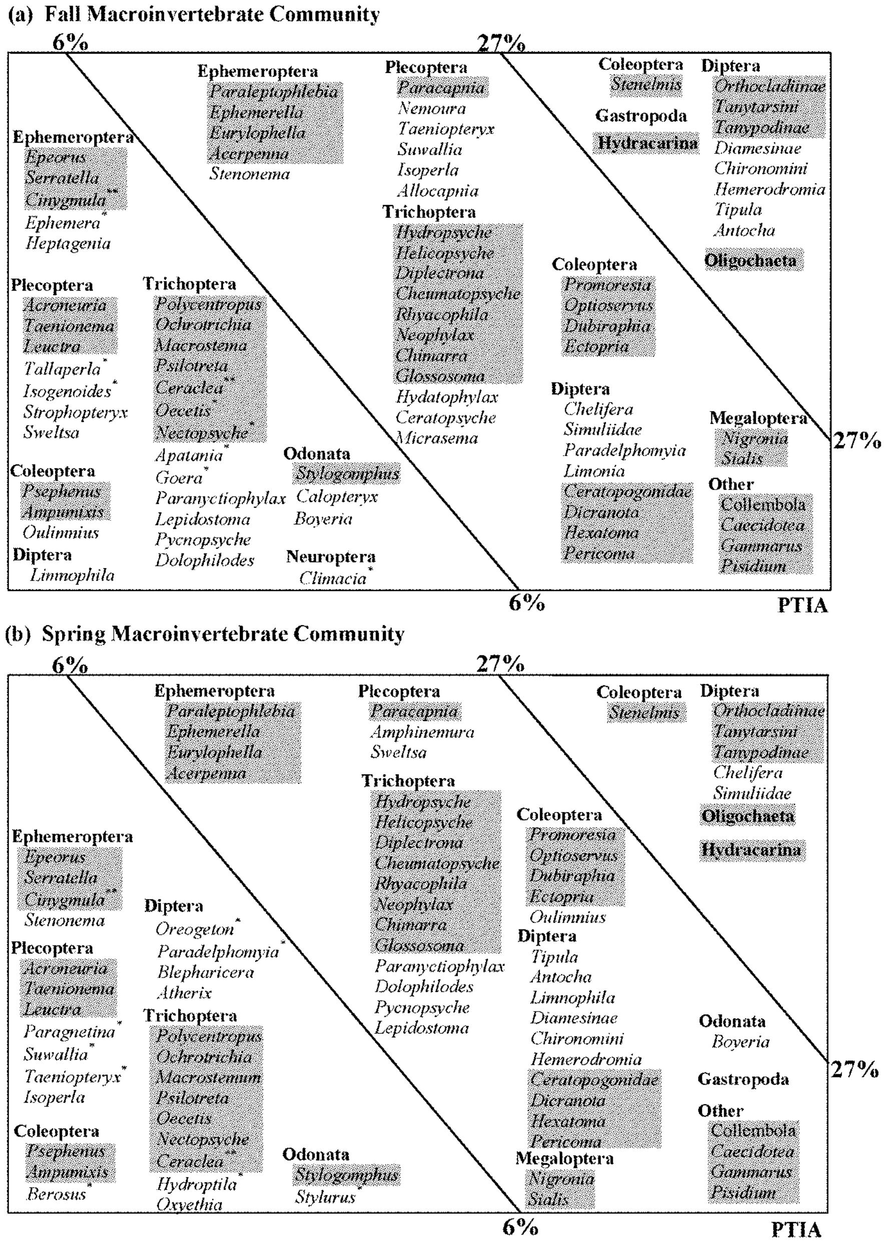

Figure 10. Presence/absence diagram for benthic macroinvertebrate taxa found in all 20 study streams during the (a) fall and (b) spring. Taxa are present in all sections moving from right to left (e.g. taxa found in the >27% PTIA range were also found in the 6–27% and <6% ranges of PTIA). Shaded blocks indicate taxa that were present in the same PTIA range in both seasons. Unique taxa, defined as present in only one sample within a season, are indicated by an asterisk. Although taxa found to be unique varied seasonally, those catchments in the <6% PTIA range consistently contained 10 unique taxa as opposed to the lower number present in the 6–27% range (two in the fall and one in the spring), and the absence of any unique taxa within the >27% range (Airport I).

ure 9). The densities of the elmid beetles *Optioservus* and *Stenelmis* were not significantly related to PTIA, and comprised the majority of the Coleoptera from catchments with >6% PTIA (Figures 9 and 10).

The Diptera occurred in relatively high densities across the entire PTIA gradient (Figure 9). The Orthocladiinae was the greatest contributor to total densities of both the Diptera and the Chironomidae (Figure 9). The density of the Orthocladiinae was unrelated to PTIA (Table V), whereas the density of Tanytarsini and Chironomini (fall, spring) and Tanypodinae (spring) all showed a negative relationship with PTIA (Table IV). The densities of the Simuliidae and *Hexatoma* (Tipulidae) showed a negative relationship with PTIA (Table IV). The densities of the remaining common Diptera were apparently unrelated to PTIA (Table V).

Both total insect and EPT taxonomic richness were correlated with most physical and water quality variables. The strongest relationships existed between EPT taxonomic richness and specific conductance, QHI and riparian width in the fall (r^2 = 0.72, 0.50, 0.46, respectively) and spring (r^2 = 0.82, 0.46, 0.50, respectively), and total insect richness and specific conductance in the fall (r^2 = 0.64) and spring (r^2 = 0.74). There was no relationship between total insect or EPT taxonomic richness and D_{50} particle size.

Using the general criteria based on insect taxonomic richness suggested by Plafkin *et al*. (1989), our study catchments with <6% PTIA were rated as ‘non-impacted’. Jones and Reed Brooks (PTIA = 5%) were similar to reference catchments in terms of total and EPT taxa richness (Figures 7a–d). The majority of catchments with PTIA > 6–27% were rated as ‘moderately impacted’. Exceptions included Long Creek in the spring and Pushaw in the fall (both ‘slightly impacted’), and Brewer in the spring and Barberry Creek in the fall (both ‘severely impacted’). Airport I – the only catchment with >27% PTIA-received a rating of ‘severely impacted’ regardless of season.

4.6. Regional patterns

The relationship of habitat, water quality, and benthic insect community structure to PTIA appeared to be consistent among regions within Maine. With the exception of the outliers noted, catchments exhibited similar trends regardless of the regional location of the urban area where they were located.

5. Discussion

5.1. Insect community structure

Stream insect community-structure became simplified as PTIA increased. Reference catchments (<6% PTIA) had richer insect communities characterized by a greater variety of EPT taxa and unique taxa compared with catchments having >6% PTIA. The EPT taxa of streams with catchments having >6% PTIA (e.g.

selected species of *Acerpenna, Paracapnia, Allocapnia, Cheumatopsyche, Hydropsyche*) are moderately tolerant to pollution and anthropogenic stresses (Barbour *et al*., 1999). The insect community of Airport I, which drained the catchment with the highest proportion of urban land-cover observed in this study, was composed almost exclusively of Diptera and represented the highest level of degradation as indicated by total insect and EPT taxonomic richness. Our observation of decreasing total taxonomic richness, EPT richness, and density of common insect taxa with increasing urban land cover is consistent with results from similar studies conducted elsewhere in North America (Table I).

5.2. Habitat Quality

Similar to insect community structure, a progressive degradation of habitat quality occurred as PTIA of the study catchments increased. This trend is consistent with past studies of the influence of urbanization on streams (Booth and Reinelt, 1993; Richards *et al*., 1993; Shaver *et al*., 1994; May, 1996; Maxted, 1996). Booth and Reinelt (1993) evaluated the habitat quality of 140 km of stream channel in Washington state, using a multimetric qualitative index similar to the QHI, and found that nearly all stream reaches influenced by >8% PTIA were classified as having the lowest habitat quality. May (1996) used a modified QHI to evaluate over 90 stream reaches covering a PTIA range of 0–60%. He found that habitat quality ranged from ‘excellent’ to ‘poor’ within the range of PTIA that corresponded to this study (1–31%). The results of May (1996) and Booth and Reinelt (1993) contrast with the results of our study in which all stream reaches had habitat quality ratings exceeding the lowest categorical values. A similar contrast occurred for the assessment of channel stability. Booth and Reinelt (1993) found that all reaches surveyed with >10% PTIA were generally unstable, whereas the majority of reaches surveyed in our study were relatively stable, regardless of PTIA.

Although decreasing habitat quality with increasing PTIA was detected, we failed to detect consistent alterations in stream channel form as a function of PTIA. For example, channel widening and incision, both widely reported to occur as urban development intensifies (Leopold, 1968; Hammer, 1972; Krug and Goddard, 1986; Robinson, 1976; Booth, 1989, 1990), were not detected in our study. The lack of evidence of changes in channel morphology due to increasing PTIA in the present study may be related to criteria used for stream selection. Cobble riffles were required to be present in all study reaches in order to reduce variability of the benthic insect communities resulting from habitat effects. Choosing only streams with cobble riffles may have resulted in the selection of streams for which the effect of increasing PTIA on habitat quality was not as great a factor because of the presence of bank material offering increased stability and natural resistance to erosion.

5.3. Water quality

The relationship between stream water quality and urbanization shown in our study was similar to that between habitat quality and urbanization. Base-flow water quality declined as PTIA increased, but this decline was manifested as relatively small and incremental changes. For example, even in the worst case scenario, DO concentrations rarely dropped below the 5 mg L^{-1} threshold often used to indicate environmentally significant low DO concentrations (Roesner, 1982). Similarly, NO_3-N concentrations almost never attained levels that could be considered a significant environmental problem. Only Pushaw contained an average NO_3-N concentration >0.6 mg L^{-1}, the concentration identified by the USGS as the national background level in streams (USGS, 1999). The results of our study, like those of similar studies, indicate that minimal water quality degradation occurs with increasing urban intensity when samples are taken during baseflow (Benke *et al.*, 1981; Garie and MacIntosh, 1986; Jones *et al.*, 1996). Our results are consistent with those of May *et al.* (1997), who reported significant water quality problems occurred only for streams draining catchments with >45% PTIA, a level of urban intensity greater than those found within this study.

5.4. Habitat quality, water quality, and insect community structure

The fundamental relationship between habitat characteristics and stream insect community structure (Ward, 1992) suggests that the decline in habitat quality as PTIA increased was a factor determining the parallel decrease in insect taxonomic richness. It should be noted, however, that streams with unusually high or low values for the QHI (Airport I, Long Creek, Airport II, and Brewer) or SRISCI (Jones Brook, Airport II, and Brewer) did not have noticeably greater or lesser taxonomic richness of their insect communities.

Because of the occurrence of high densities of Chironomidae and *Hydropsyche* in the more urbanized catchments, it may be inferred that increased sedimentation contributed to the simplification of insect community structure as PTIA increased. This is because some taxa of the Chironomidae (Merritt and Cummins, 1996) and *Hydropsyche* (Runde and Hellenthak, 2000) are known to tolerate high levels of silt. Nevertheless, even the maximum TSS concentrations observed in this study were low compared with levels considered to be environmentally damaging (<10 mg L^{-1}; Marsh, 1991). Furthermore, results of the pebble count procedure also indicated that D_{10} particle size was not significantly related to PTIA which indicates that sedimentation was not a major environmental problem at the study sites.

Duda *et al.* (1982), Whiting and Clifford (1983), and Pratt *et al.* (1981) all suggested that degraded water quality resulting from runoff containing non-point source (NPS) pollution was the causative agent for the degradation of the insect communities in the urban streams they studied (Table I). In our study, specific conductance showed a strong positive relationship with PTIA ($r^2 = 0.74$). This implies that increased levels of chronic NPS pollution, due to dissolved materials such as salt and heavy metals, enters streams in runoff from roads and parking lots as urban land-cover increases. Pitt *et al*. (1995) noted that the effects of urban runoff on biota are rarely from acute toxicity but rather from long-term chronic exposure. Chronic NPS pollution could contain contaminants responsible for the simplification of stream insect communities as PTIA increased. Yet, because streams with unusually high specific conductance (Brewer), TSS (Long Creek), or NO_3-N (Pushaw) did not have unusually low levels of taxonomic richness of their insect communities, the relationship between potential NPS and insect community structure remains unclear.

We emphasize that significant relationships between attributes of insect community and the various indices of habitat and water quality cannot be considered indicative of causation due to the correlative nature of this study. Each of these categories of variables may show parallel responses to the effects of increasing urban land-cover.

5.5. The PTIA threshold

In the context of this study, PTIA is probably best considered a cumulative indicator of the many influences of urbanization on stream ecosystems. This is reflected by the correlation between increasing PTIA and the degradation of stream habitat quality, water quality, and insect community structure (Table I). Rather than a continuous relationship between attributes of insect community structure and PTIA, however, the relationship appeared to be best described as a step function, with abrupt changes occurring at an apparent threshold of PTIA. This threshold effect is manifested by an abrupt change in the taxonomic richness of stream insect communities at a specific level of PTIA, followed by a relatively constant levels of richness as PTIA departs from this level (Klein, 1979; Schueler, 1994; Arnold and Gibbons, 1996; May *et al*., 1997). Previous studies reported threshold levels ranging from 5–25% PTIA (Table I). Our study supports the conclusions of these studies by showing an abrupt change in stream insect community structure at approximately 6% PTIA. Total taxa richness and EPT richness showed sudden decreases when catchment PTIA increased above 6% PTIA. Furthermore, no statistical difference was found in total or EPT richness as PTIA increased from 6 to 27%, indicating that once the 6% PTIA threshold was exceeded, there was little further change in insect community structure.

It is uncertain whether the difference in the range of apparent PTIA thresholds reported by different studies (5–25%, Table I) is ecologically significant because of potential differences in the accuracy of available PTIA conversion factors (Klein, 1979; Schueler, 1994; Arnold and Gibbons, 1996; May *et al*., 1997; Morse 2001). Nevertheless, a threshold response by insect community structure as catchment PTIA increases generally should be expected (Table I). Although there is little information concerning processes underlying this phenomenon, we speculate that it may be related to the implementation of storm sewer systems as urbanization intensifies. This may result in an abrupt and radical change to the hydrological regime of an urbanizing catchment, which will have an important effect on insect community structure due to the fundamental relationship between discharge and habitat attributes (cf. Townsend *et al.*, 1997; Walsh *et al.*, 2001). Understanding relationships between the hydrological regime of urban streams and their biotic communities is critical to the restoration and management of these systems (Walsh *et al.*, 2001). Measurement of PTIA was found to be a reliable quantitative index for predicting the response of stream ecosystems to urbanization in central and southern Maine. Given the sensitivity of stream communities to PTIA, resource managers within the northeastern United States should be encouraged to use PTIA based indicators to identify streams likely to be affected by urbanization.

Acknowledgements

We wish to acknowledge Jeff Dennis, Leon Tsomides, and Mary Dennis of the Maine Department of Environmental Protection for assistance in finding study catchments and for funding, in part, the PTIA analyses. The Natural Resources Conservation Service provided the aerial photos for the PTIA analyses. Bill Cook and Bob Hoskins (Maine Soil and Water Analytical Laboratory) conducted the chemical analyses of water samples. Mike Chadwick and Tom Woodcock, University of Maine, assisted with the identification of invertebrates and field work. Shane Gebauer and Stephanie Vermillion, University of Maine, assisted in the field. Sean Murphy, Jeff Hepinstall, and the Maine Image Analysis Lab, University of Maine, helped conduct the analyses of satellite imagery. Finally, we wish to acknowledge the assistance of Chris May of the University of Washington for his assistance in the conceptualization and design of the study. This is publication number 2584 of the University of Maine Agriculture and Forestry Research Station.

References

Arnold, D. G., Boison, P. J. and Patton, P. C.: 1982, 'Sawmill Brook: An example of rapid geomorphic change related to urbanization', *J. Geol.* **90**, 155–166.

Arnold, D. G. and Gibbons C. J.: 1996, 'Impervious surface coverage – The emergence of a key environmental indicator', *J. Amer. Plann. Assoc.* **62**, 243–258.

Barbour, M. T., Gerritsen, J., Snyder, B. D. and Stribling, J. B.: 1999, *Rapid Bioassessment Protocols for Use in Streams and Wadable Rivers: Periphyton, Benthic Macroinvertebrates and Fish*, 2nd ed., EPA 841-D-99-002, U.S. Environmental Protection Agency, Washington, D.C.

Barbour, M. T. and Stribling, J. B.: 1994, 'A Technique for Assessing Stream Habitat Structure', in *Proceedings of Riparian Ecosystems of the Humid U.S: Management, Function, and Value*, National Association of Conservation Districts, Washington, D.C.

Benke, A. C., Willeke, F. P. and Stites, D.: 1981, 'Effects of Urbanization on Stream Ecosystems', *Completion Report Project No. A-055-0A*, Office of Water Research and Technology, U.S. Department of Interior.

Booth, D.: 1989, 'Runoff and stream-channel changes following urbanization in King County, Washington', *Washington Div. Geol. Earth Resour. Bull.* **78**, 639–650.

Booth, D.: 1990, 'Stream-channel incision following drainage-basin urbanization', *Water Resour. Bull.* **26**, 407–417.

Booth, D.: 1991, 'Urbanization and the natural drainage system – Impacts, solutions, and prognoses', *Northw. Environ. J.* **7**, 93–118.

Booth, D. and Reinelt, L. E.: 1993, 'Consequences of Urbanization on Aquatic Systems-measured Effects, Degradation Thresholds, and Corrective Strategies', in *Proceedings Watershed '93. A National Conference on Watershed Management*, 21–24 March 1993, Alexandria, Virginia, pp. 545–550.

Brown, A. V. and Brussock, P. B.: 1991, 'Comparison of benthic invertebrates between riffles and pools', *Hydrobiologia* **220**, 99–108.

City of Olympia, Washington: 1994, *Impervious Surfaces Reduction Study: Technical and Policy Analysis Final Report*, City of Olympia Public Works Department.

Commission for Environmental Cooperation: 1994, *Ecological Regions of North America, Level II*, Commission for Environmental Cooperation, Montreal, Quebec, Canada.

DeLorme: 1997, *The Maine Atlas and Gazeteer*, DeLorme, Yarmouth, Maine.

Duda, A. M., Lenat, D. R. and Penrose, D. L.: 1982, 'Water quality in urban streams – What can we expect?' *J. Water Pollut. Contr. Federat.* **54**, 1139–1147.

Garie, H. L. and MacIntosh, A.: 1986, 'Distribution of benthic macroinvertebrates in a stream exposed to urban runoff', *Water Resour. Bull.* **22**, 447–455.

Gore, J. A.: 1996, 'Discharge Measurements and Streamflow Analysis', in F. C. Hauer and G. A. Lamberti (eds), *Methods in Stream Ecology*, Academic Press, San Diego, California.

Hammer, T. R.: 1972, 'Stream channel enlargement due to urbanization', *Water Resour. Res.* **8**, 1530–1540.

Hepinstall, J. A., Sader, S. A, Krohn, W. B., Boon, R. B. and Bartlett, R. I.: 1999, 'Development and Testing of a Vegetation Land Cover Map of Maine', *Maine Agricult. Forest Exper. Station Techn. Bull.* **173**.

Hollis, G. E.: 1975, 'The effect of urbanization on floods of different recurrence intervals', *Water Resour. Res.* **66**, 84–88.

Hynes, H. B. N.: 1975, 'The stream and its valley', *Verh. Internat. Verein. Limnol.* **19**, 1–15.

Jones, R. C. and Clark, C. C.: 1987, 'Impact of watershed urbanization on stream insect communities', *Water Resour. Bull.* **23**, 1047–1055.

Klein, R. D.: 1979, 'Urbanization and stream quality', *Water Resour. Bull.* **15**, 948–963.

Krug, W. R. and Goddard, G. L.: 1986, *Effects of Urbanization on Streamflow, Sediment Loads, and Channel Morphology in Pheasant Branch Basin Near Middleton, Wisconsin*, U.S. Geological Survey, Water-Resources Investigation Open-File Report 85-4068, 82 pp.

Leopold, L. B.: 1968, *The Hydrologic Effects of Urban Land Use: Hydrology for Urban Land Planning – A Guidebook of the Hydrologic Effects of Land Use*, U.S. Geological Survey Circular No. 554.

Logan, P. and Brooker, M. P.: 1983, 'The macroinvertebrate faunas of riffles and pools', *Water Res.* **17**, 293–260.

Marsh, W. M.: 1991, *Landscape Planning Environmental Applications*, 2nd ed., John Wiley & Sons, Inc., New York City, New York.

Maxted, J. R.: 1996, 'The Use of Impervious Cover to Predict Ecological Condition of Wadeable Nontidal Streams in Delaware', in *Proceedings from National Symposium*, Chicago, Illinois.

May, W. M.: 1996, 'The Cumulative Effects of Urbanization on Small Streams in the Puget Sound Lowland Ecoregion', *Ph.D. Thesis*, University of Washington.

May, W. M., Horner, R. R., Karr, J. B., Mar, B. W. and Welch, E. B.: 1997, 'Effects of urbanization on small streams in the Puget Sound Lowland Ecoregion', *Watersh. Protect. Techn.* **2**, 483–494.

Meader, M. R., Hupp, C. R., Cuffney, T. E. and Gurtz M. E.: 1993, *Methods for Characterizing Stream Habitat as Part of the National Water-Quality Assessment Program*, U.S. Geological Survey Open-File Report 93-408.

Merritt, R. W. and Cummins, K. W. (eds): 1996, *An Introduction to the Aquatic Insects of North America*, 3rd ed., Kendall/Hunt, Dubuque, Indiana.

Morse, C. C.: 2001, 'The Response of First and Second Order Streams to Urban Land-use in Maine, U.S.A.', *M.Sc. Thesis*, Ecology and Environmental Science Program, The University of Maine, Orono, Maine, U.S.A.

O'Hara, F.: 1997, *The Cost of Sprawl*, State of Maine, Executive Department, State Planning Office, 20 p.

Pedersen, E. R. and Perkins, M. A.: 1986, 'The use of benthic invertebrate data for evaluating impacts of urban runoff', *Hydrobiologia* **139**, 13–22.

Peiser, R. B.: 1989, 'Density and urban sprawl', *Land Econom.* **65**, 194–204.

Pfankuch, D. J.: 1975, *Stream Reach Inventory and Channel Stability Evaluation*, U.S. Department of Agriculture Forest Service, Region 1, Missoula, Montana.

Pitt, R., Field, R., Lalor, M. and Brown, M.: 1995, 'Urban stormwater toxic pollutants: Assessment, sources, and treatability', *Water Environ. Res.* **67**, 260–275.

Plafkin, J. L., Barbour, M. T., Porter, K. D., Gross, S. K. and Hughes, R. M.: 1989, *Rapid Bioassessment Protocol for Use in Streams and Rivers: Benthic Macroinvertebrates and Fish*, U.S. Environmental Protection Agency, 440-4-89-001.

Platts, W. S., Megehan, W. F. and Minshall, G. W.: 1983, *Methods for Evaluating Stream, Riparian, and Biotic Conditions*, U.S. Department of Agriculture Forest Service, Washington, D.C.

Porcella, D. B. and Sorenson, D. L.: 1980, *Characteristics of Nonpoint Source Urban Runoff and its Effect on Stream Ecosystems*, U.S. Environmental Protection Agency, 600-3-80-032.

Potyondy, J. P. and Hardy, T.: 1994, 'Use of pebble counts to evaluate fine sediment increase in stream channels', *Water Resour. Bull.* **30**, 509–520.

Pratt, J. M., Coler, R. A. and Godfrey, P. J.: 1981, 'Ecological effects of urban stormwater runoff on benthic macroinvertebrates inhabiting Green River, Massachusetts', *Hydrobiologia* **83**, 29–42.

Ragan, R. M., Dietman, R. J. and Moore, R. A.: 1977, 'The impact of urbanization on stream quality', *Internat. Assoc. Hydrolog. Sourc. Public.* **123**, 324–333.

Richards, C., Host, G. E. and Arthur, J. W.: 1993, 'Identification of predominant environmental factors structuring stream macroinvertebrate communities within a large agricultural catchment', *Freshw. Biol.* **29**, 285–294.

Robinson, A. M.: 1976, 'The Effects of Urbanization on Stream Channel Morphology', *National Symposium of Urban Hydrology, Hydraulics, and Sediment Control, Lexington, Kentucky*.

Roesner, L. A.: 1982, 'Quality of Urban Runoff', in D. F. Kibler (ed.), *Urban Stormwater Hydrology, Water Resources Monograph 7*, American Geophysical Union, Washington, D.C.

Rosenberg, D. M. and Resh, V. H.: 1993, *Freshwater Biomonitoring and Benthic Macroinvertebrates*, Chapman and Hall, New York City, New York.

Runde, J. M. and Hellenthak, R. A.: 2000, 'Behavioral responses of *Hydropsyche sparna* (Trichoptera: Hydropsychidae) and related species to deposited bedload sediment', *Environ. Entomol.* **29**, 704–709

Schueler, T. R.: 1992, 'Mitigating the Adverse Impacts on Urbanization on Streams: A Comprehensive Strategy for Local Government', in P. Kumble and T. R. Schueler (eds), *Watershed Restoration Sourcebook, Publication #92701*, Metropolitan Washington Council of Government, Washington, D.C.

Schueler, T. R.: 1994, 'The importance of imperviousness', *Watersh. Protect. Techn.* **1**, 100–111.

Shaver, E. J., Maxted, G. C. and Carter, D.: 1995, 'Watershed Protection Using an Integrated Approach', in *Stormwater NPDES Related Monitoring Needs*, Engineering Foundation, American Society of Civil Engineers, Crested Butte, Colorado, 7–12 August 1994.

Soil Conservation Service: 1975, *Urban Hydrology for Small Watersheds*, U.S. Department of Agriculture Soil Conservation Service Technical Release No. 55, Washington, D.C.

Stanford, J. A.: 1996, 'Landscapes and Catchment Basins', in F. C. Hauer and G. A. Lamberti (eds), *Methods in Stream Ecology*, Academic Press, San Diego, California.

Stewart, K. W. and Stark, B. P.: 1993, *Nymphs of North American Stonefly Genera (Plecoptera)*, University of North Texas Press, Denton, Texas.

Thorp, J. H. and Covich, A. P.: 1991, *Ecology and Classification of North American Freshwater Invertebrates*, Academic Press, New York City, New York.

Townsend, C. R., Scarsbrook, M. R. and Dolédec, S.: 1997, 'The intermediate disturbance hypothesis, refugia, and biodiversity in streams', *Limnol. Oceanogr.* **42**, 938–949.

U.S. Geological Survey (USGS): 1999, *The Quality of our Nation's Water – Nutrients and Pesticides*, U.S. Geological Survey Circular 1225, 82 pp.

Vesterby, R. E.: 1994, 'Urbanization of Rural Land in the United States', *Agricultural Economic Report No. 673*, U.S. Department of Agriculture, Washington, D.C.

Walsh, C. J., Sharpe, A. K., Breen, P. F. and Sonneman, J. A.: 2001, 'Effects of urbanization on streams of the Melbourne region, Victoria, Australia. I. Benthic macroinvertebrate communities', *Freshw. Biol.* **46**, 535–554.

Ward, J. V.: 1992, *Aquatic Insect Ecology. 1. Biology and Habitat*, John Wiley & Sons, New York.

Whipple, W., DiLouie, J. B. and Pytlar, T.: 1981, 'Erosion potential of streams in urbanizing areas', *Water Res. Bull.* **17**, 36–45.

Whiting, E. R. and Clifford, H. J.: 1983, 'Invertebrates and urban runoff in a small northern stream, Edmonton, Alberta, Canada', *Hydrobiologia* **102**, 73–80.

Wiggins, G. B.: 1977, *Larvae of the North American Caddisfly Genera (Trichoptera)*, University of Toronto Press, Toronto, Ontario.

Wolman, M. G.: 1954, 'A method of sampling coarse river-bed material', *Transact. Amer. Geophys. Union* **35**, 951–956.

Wolman, M. G. and Schick, A. P.: 1967, 'Effects of construction on fluvial sediment, urban and suburban areas of Maryland', *Water Resour. Res.* **3**, 451.